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1976   J R BAYLESS, J P HECKL

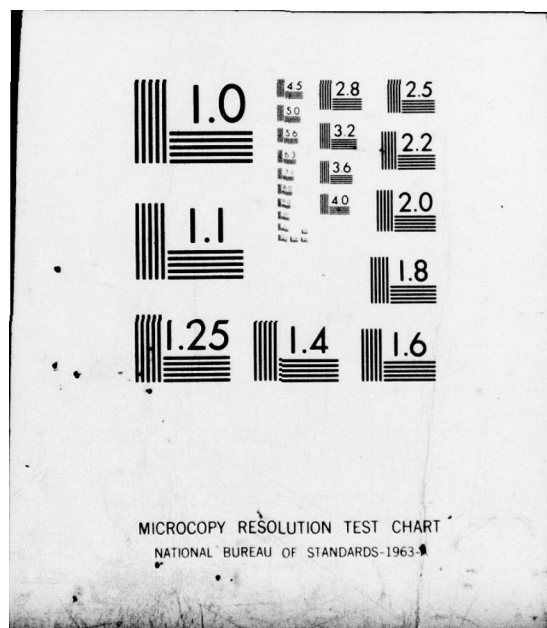UNCLASSIFIED   NL

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The liquid metal plasma valve (LMPV) is a high average power mercury vacuum-arc switching device. It has been extensively developed over the past ten years as a converter valve for use by the electric utilities industry at nominal average power levels of 90 MW. This paper will describe an LMPV closing switch now under development for operation in conjunction with a PFN to deliver 1 MW average power to a load in 20 to 50 μsec pulses at up to 100 kV. The objective of this development is to obtain information for the design of switches capable of operating at much higher power levels.

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THE LIQUID METAL PLASMA VALVE CLOSING SWITCH

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ABSTRACT

The liquid metal plasma valve (LMPV) is a high average power mercury vacuum-arc switching device. It has been extensively developed over the past ten years as a converter valve for use by the electric utilities industry at nominal average power levels of 90 MW. This paper will describe an LMPV closing switch now under development for operation in conjunction with a PFN to deliver 1 MW average power to a load in 20 to 50 μsec pulses at up to 100 kV. The objective of this development is to obtain information for the design of switches capable of operating at much higher power levels.

Introduction

The increasing size and complexity of pulsed power systems is leading to the requirement for closing switches capable of higher average powers, peak currents and voltages while maintaining high reliability and compactness. Of all the existing types of closing switch, only thyratrons and possibly high-power spark gaps can approach operation at 1 MW average power under the typical conditions outlined in the first column of the table; present designs show little promise of being scalable to the higher power levels which will ultimately be required. The liquid metal plasma valve closing switch (LMPVCS), which offers an effective alternative for fulfillment of these future requirements, is a high average power vacuum-arc device employing a mercury vapor plasma as the current conduction medium. The liquid metal plasma valve (LMPV) has been developed over the past ten years primarily as a high power converter for the electric utilities industry in high voltage direct current (HVDC) power transmission at the levels outlined in the second column of the table. The last column of the table outlines the ratings of the LMPV used in an existing circuit breaker system. The capability of the LMPV to operate at high average currents in converter applications, which are more than ten times those achieved with any existing closing switch, has provided the impetus for the development of the LMPVCS discussed in this paper.

Table 1. Switch Specifications

Parameter	Closing Switch Parameters	HVDC LMPV Converter Rating	LMPV Circuit Breaker Rating
Peak Voltage	50-200 kV	150 kV nominal	30 kV
Pulse Width	20-50 μsec	6 msec	20 msec
Peak Current	8-4 kA	1.8 kA nominal	15 kA
Average Current	40-10 A	600 A nominal	low
Repetition Rate	250-50 Hz	60 Hz	30 per hour
Average Power Delivered to Load	1 MW	90 MW	low
Run Time	1 min	Continuous	Continuous

The LMPVCS development program is directed toward the demonstration of a new type of closing switch capable of delivering 1 MW average power to a load under the test conditions outlined in the first column of the table. While 1 MW gives an average current level well below the present capabilities of the LMPV, closing switch operation is different from that for a converter valve for which the existing hardware has been designed and tested. For this reason, feasibility will first be demonstrated at 1 MW and the data thus generated will serve as the basis for scaling to higher power levels.

LMPV Principle

The LMPV[1] shown schematically in Figure 1 basically consists of a liquid metal cathode structure[2], an anode, and a condenser. The water cooled cathode is formed from molybdenum and contains a narrow annular groove into which mercury is fed at a controlled flow rate. Arc spots form on the inner and outer periphery of the cathode groove such that the arc power is distributed and maximum cooling results. Furthermore, the molybdenum becomes wetted by the mercury so that the arc spots are anchored at the mercury-molybdenum interface, thereby eliminating droplet ejection and insuring gravity independence. The cathode is maintained at a temperature of 20-30°C for which mercury vaporization from the small mercury surface area during arc operation is minimal. The anode temperature is kept sufficiently high that mercury does not condense on it and the condenser is kept cold enough to condense mercury vapor released from the cathode. Thus, a low pressure is maintained and the valve operates in the vacuum arc mode. This permits a low voltage drop during conduction combined with high recovery rates and excellent insulation integrity.

The use of this liquid metal cathode in which the arc spots are anchored and mercury evaporation is controlled eliminates a number of the main problems associated with the conventional use of mercury as a discharge cathode. For example, with a conventional device, such as an ignitron, which employs an extensive mercury pool, the evaporation of cathode material from the surface is significant; it greatly exceeds the efflux of mercury from the cathode spot itself. Furthermore, as the cathode spot moves erratically over the mercury surface, mercury droplets are ejected into the interelectrode space where they vaporize and cause a significant addition to the neutral vapor density. The resultant pressure combined with the Paschen and vacuum breakdown relationships result in relatively inferior high voltage and recovery properties for these devices in comparison to the LMPV.

LMPV conduction is initiated by igniter electrodes which create a burst of plasma at the cathode surface. While the plasma bridges the electrodes, the conduction voltage is characteristically low, ranging from 20 to 40 V. The extinction of electron emission from the cathode spot is complete within a 10 ns after current zero. Particle velocities away from the cathode can be superthermal[3] so that total decay of the plasma bridge occurs in tens of microseconds. When the plasma is dissipated, the valve can be subjected to rapidly rising forward voltages. While the plasma is still present, although no longer being created in the cathode spot region, the application of a reverse voltage can be withstood by the valve immediately following current zero because anode arc spots are not easily formed.

LMPVCS System Design

A block diagram of the LMPVCS system is shown in Figure 2. The LMPV, which is the heart of this system, is shown in Figure 3 as it is being prepared for bakeout. The electrical and fluid connections to the cathode can be seen in the lower portion of Figure 3. The bulk of the device consists of the cylindrical condenser and its coolant manifold. Two 8 liter/sec Vac Ion pumps, which are shown extending from the lower portion of the condenser, are provided in order to remove any gas evolved during LMPV operation. The anode shaft and its supporting ceramic bushing are mounted at the upper end of the condenser. The LMPV is assembled with great care under clean conditions. This is followed by bakeout under vacuum and pinch off to yield a final pressure of 10^{-9} Torr prior to the introduction of mercury.

The positive high voltage lead is connected to the anode which is insulated from the rest of the LMPVCS system by the ceramic bushing which, in turn, is enclosed within a 70 cm long fiberglass tube filled with dielectric fluid and fitted with corona rings. The anode is constructed of arc-cast molybdenum due to its insensitivity to arc errosion. This component receives approximately 70% of the power in the discharge. This dissipation can be divided into a part associated with ignition (anode fall period) and a part resulting from conduction.

Conservatively assuming an anode fall time (time required for anode voltage to drop from a high value prior to conduction to the conduction value of 40 volts or less) of $0.5\ \mu sec$ and a current rise time of $2\ \mu sec$, the total power input to the anode under the most severe conditions noted in the first column of the table is 3.3 kW. This is removed by the anode temperature control subsystem consisting of a liquid loop which circulates Dowtherm at a temperature of up to $80^{\circ}C$ through the anode at 5 gal/min. The elevated temperature of the coolant insures that mercury does not condense on the anode, thereby avoiding formation anode arc spots in the event of voltage polarity reversal. The coolant flow rate is sufficient to operate with less than a $20^{\circ}C$ temperature rise during initial LMPV processing at continuous anode power levels of up to 10 kW, as well as under pulsed testing at lower levels. High voltage isolation of the bulk of this subsystem, which is near ground potential, is provided by teflon hoses and the excellent dielectric properties of Dowtherm.

The condenser consists of a double walled stainless steel structure through which coolant is circulated in order to maintain an inner wall temperature below $-7^{\circ}C$. This temperature corresponds to a mercury vapor pressure of 10^{-4} Torr which, on the basis of Paschen breakdown data, is a factor of five below that which would result in breakdown at 200 kV. The condenser temperature control subsystem consists primarily of an R11 chiller operating at 4 gal/min. which incorporates a 1-1/2 hp refrigeration unit. This chiller can remove up to 1.5 kW from the condenser at $-7^{\circ}C$. The temperature control subsystem also includes heaters which prevent condensation from forming on various exposed areas.

The cathode structure is constructed largely of molybdenum which resists arc errosion while also being easily wetted by mercury. Approximately two watts of power is deposited in the cathode per ampere of discharge current. This is removed from the cathode groove area by the cathode temperature control subsystem which circulates water at $20-30^{\circ}C$ through the cathode cooling channels. This subsystem also provides power to heaters which prevent mercury condensations in areas remote from the cathode groove.

Three igniter electrodes of different designs are located around the periphery of the active area of the cathode. They are mostly hidden within the cathode structure in order to avoid being damaged by the arc. The optimum igniter design for closing switch operation will be determined in the course of the test program following completion of the system. The igniter subsystem provides current pulses to the igniters on external command, water cooling of two of the igniters, and heater power for the third.

The mercury supply subsystem contains a reservoir of mercury suitable for $> 10^4$ one minute operations and provides a regulated flow of mercury into the cathode.

The final system will consist of a single mobile unit which only requires water, pressurized air and power for its operation.

Summary

The Liquid Metal Plasma Valve Closing Switch (LMPVCS) concept appears to be a viable approach for use in conjunction with a pulse forming network to deliver greatly in excess of 1 MW average power to a load at voltages of >100 kV (200 kV PFN charging voltage). Furthermore, it is probable that many closing switch requirements can be met with existing hardware. A program is now underway to build an LMPVCS system for use at 1 MW average power with charging voltages up to 200 kV, and to experimentally verify the feasibility of this approach and to determine its scalability.

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[3] G. M. Eckhardt, "Velocity of Neutral Atoms Emanating from the Cathode of a Steady State Low-Pressure Mercury Arc," J. Appl. Phys., 44, No. 3, March 1973.
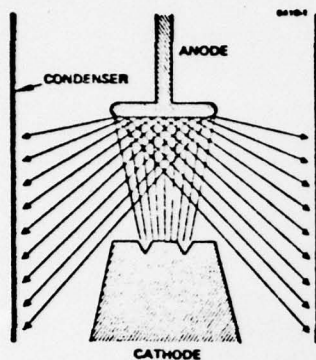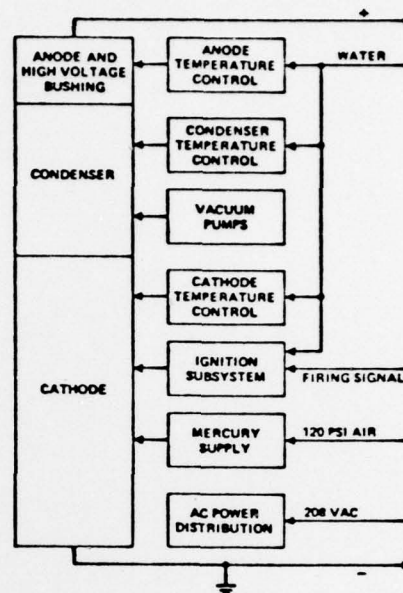
Fig. 1. Liquid Metal Plasma Valve Schematic   **Fig. 2.** Block Diagram of LMPVCS System

Fig. 3. LMPV Being Prepared for Bakeout